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Title: Progress Toward Volumetric Thermonuclear Burn with Double Shell Implosions

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Los Alamos
NATIONAL LABORATORY

Progress Toward Volumetric Thermonuclear Burn with Double Shell Implosions

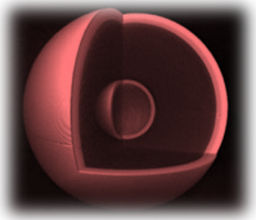
Eric Loomis,
Thermonuclear Plasma Physics (P-4)

April 29, 2021

Physics Cafe

ASET
NPAC
ANSE
HEDPF

Double Shells are a large national effort consisting of theory/modeling, fabrication, and experiment



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General Atomics

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Laboratory for Laser Energetics, University of Rochester

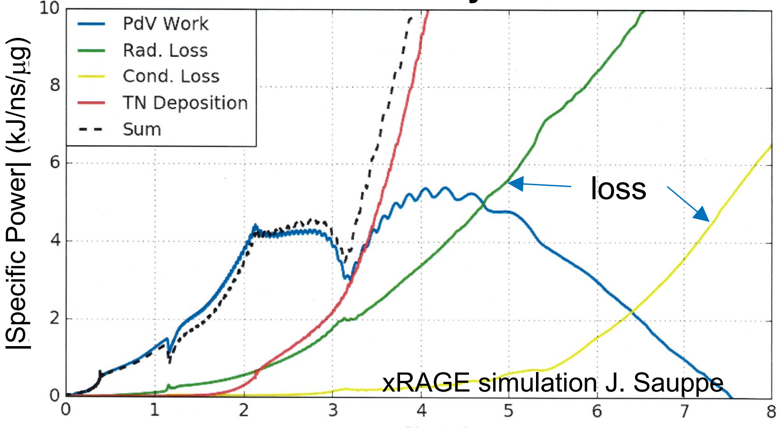
Margaret Huff
Sean Regan
Valeri Goncharov

Double Shells are funded by Campaign-10 (Inertial Confinement Fusion, John Kline Program Manager)

Early NIF double shell designs:
[*]P. Amendt, J.D. Colvin, R.E. Tipton et al, Phys. Plasmas 9 (2002)

High-Z shells offer new opportunities to assess power balance in a confined, burning plasma

How important are radiation losses in a volume burn system?



Kirkpatrick and Wheeler, Nucl. Fusion 21, 389 (1981)

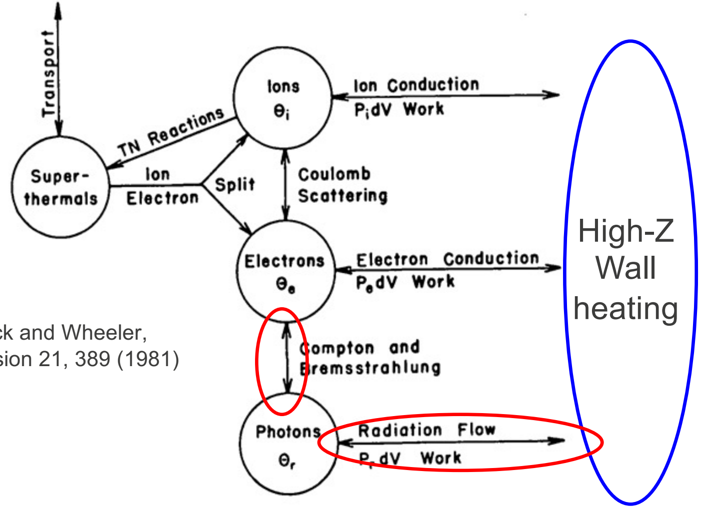
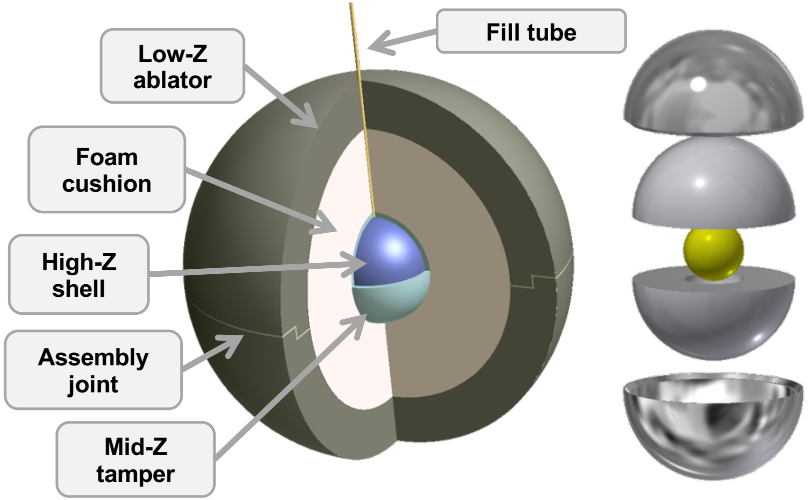


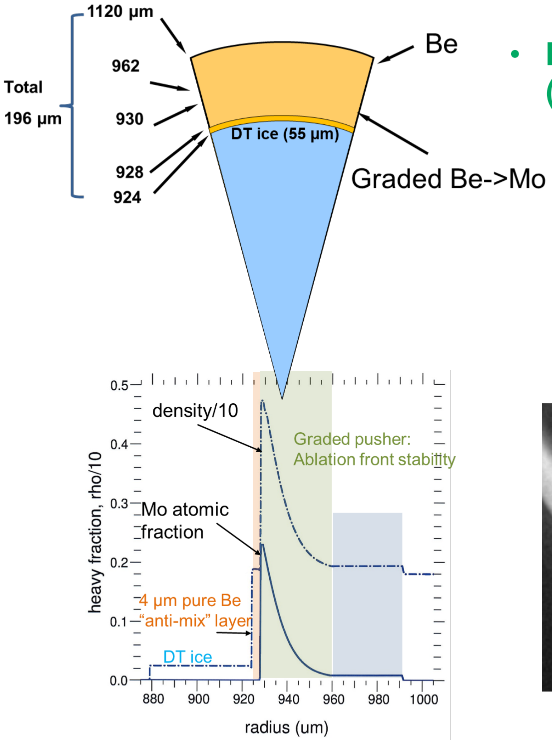
FIG.1. Energy flow diagram for a thermonuclear plasma. The term 'superthermals' is used to refer to both DT and DD reaction products and hot electrons.

How does power balance change with the introduction of high-Z mix or growing 3D surface instabilities?

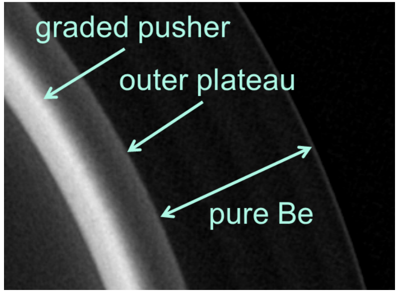
Goal of National program is to demonstrate several-fold yield amplification (alpha-heating) with high-Z shells



- **Double-Shell capsules:**
  - Lower convergence ratio of fuel to reach burn
  - Do not require sophisticated pulse shaping
  - Are more difficult to build and diagnose



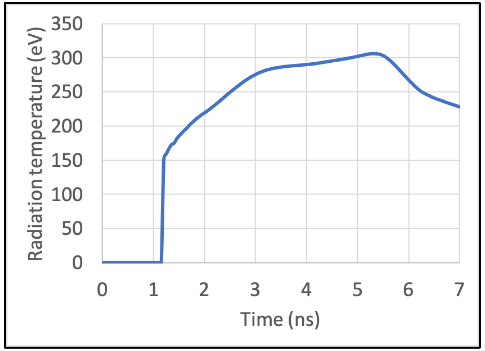
- **Pushered single shell (PSS) capsules:**
  - Utilize many design aspects of LLNL indirect-drive ICF program
  - Extension to high-Z (Cr, Mo, W) layer on inner surface

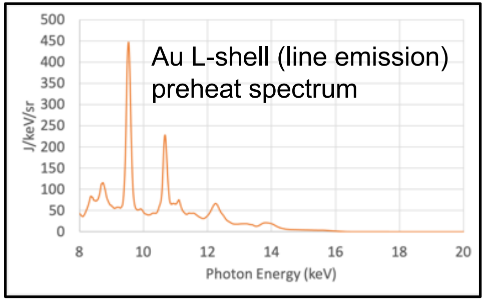


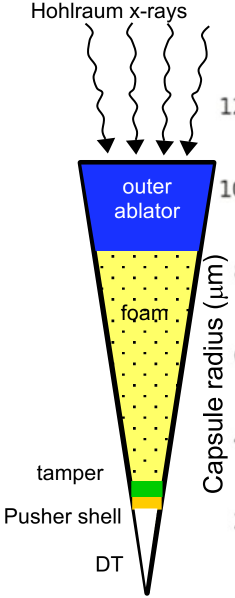
Courtesy of S. MacLaren (LLNL)

To achieve volume burn in double shell capsules requires accelerating interior high-Z pusher to 200+ km/s

Hohlraum produces thermal (top) and non-thermal (bottom) x-rays

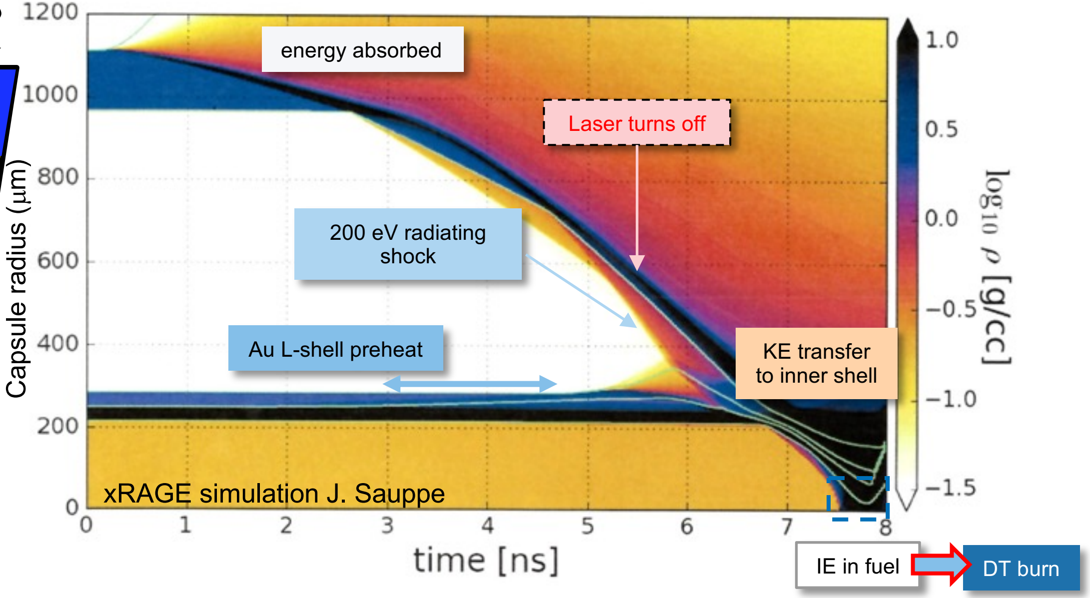




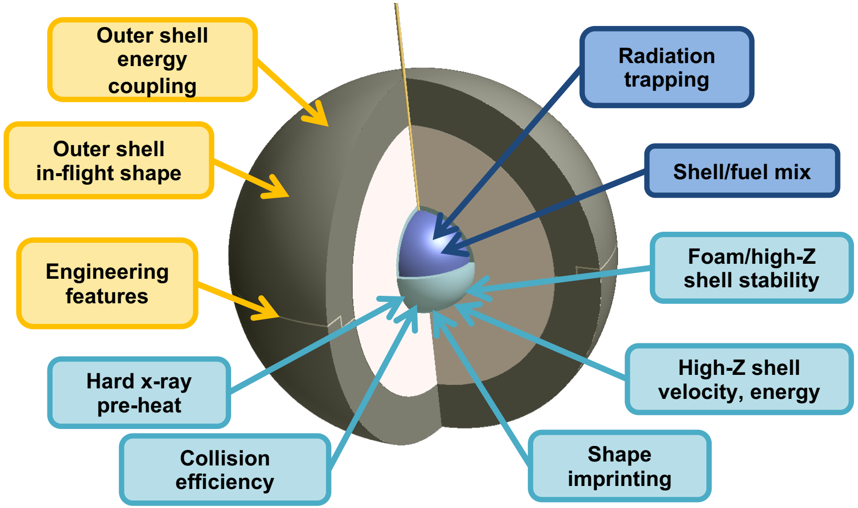


*Montgomery, Daughton et al., Phys. Plasmas 25, 092706 (2018)

Implosion trajectory of double shell capsule

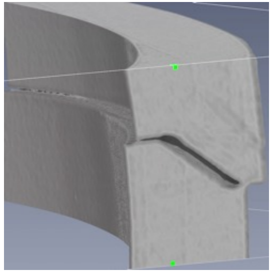


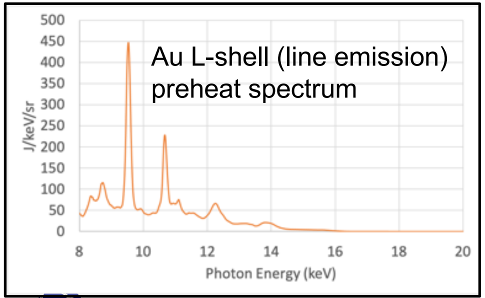
Our research is focused on understanding double shell physics from the outer shell through burn

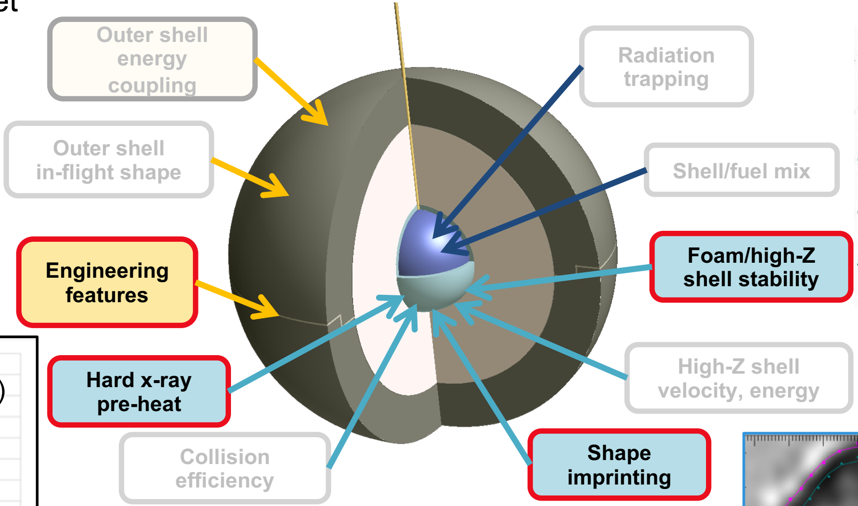


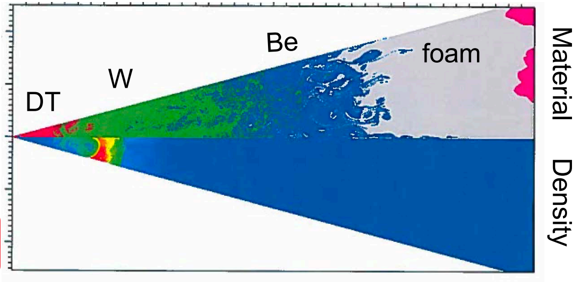
Our research is focused on understanding double shell physics from the outer shell through burn

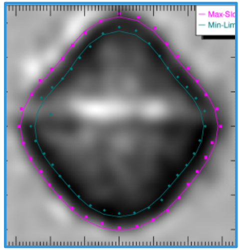
Al hemi-shell joint offset





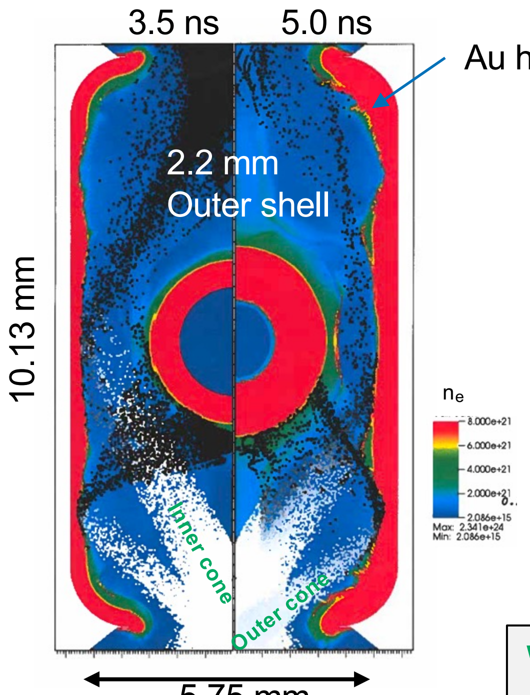






Outer shell radiography

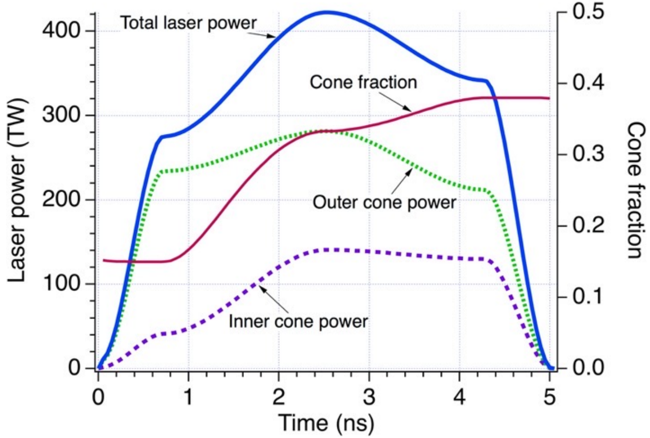
Our NIF platform uses indirect-drive and laser power balance to control symmetry



Only lower cones shown

*E.C. Merritt et al., Phys. Plasmas 26, 052702 (2019)

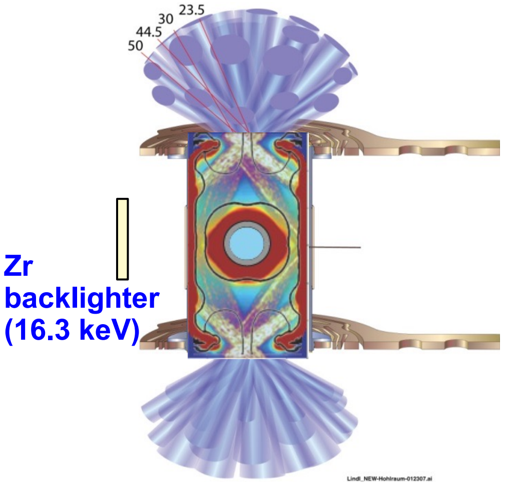
1.5 MJ laser energy pulse shape



We benefit from 10+ years of hohlraum modeling advances through indirect-drive NIF campaigns

Diagnosing symmetry uses laser-driven x-ray source

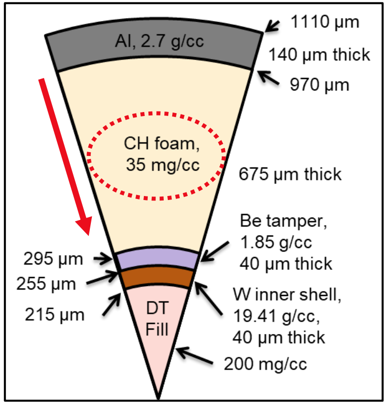
Convergent ablator platform

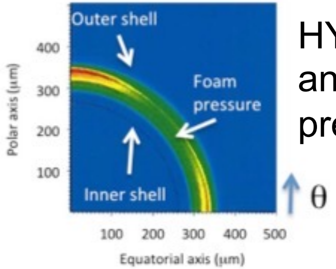


Shape imprinting

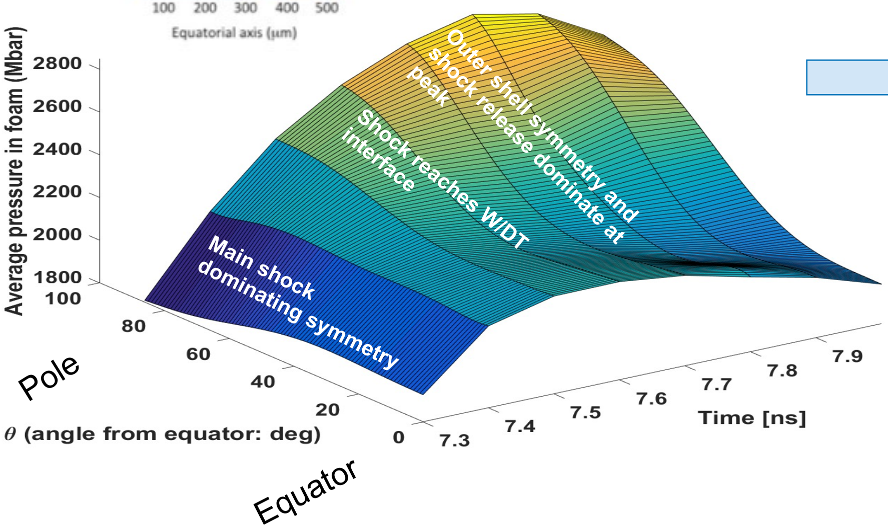
Foam pressure contour during shell collision mediates shape transfer process

Point design capsule





HYDRA (LLNL) simulation of angular variation in foam pressure between shells



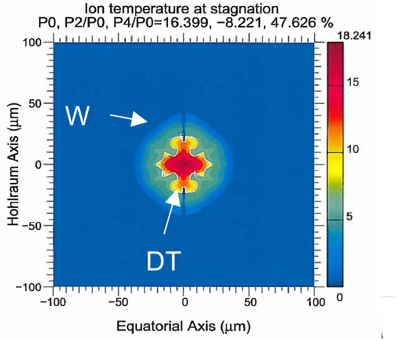
Radial impulse acceleration of inner shell

Integrate at each θ

$$\int f\,dt = m\,dv$$

$$\int pA\,dt = m\,dv$$

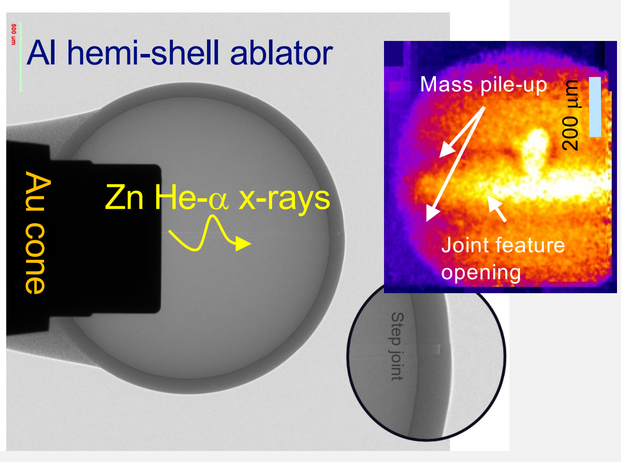
m = inner shell mass
A = inner shell surface
p = avg. foam pressure
dv = velocity increment



Engineering features

Recent NIF data has provided new insight into hydrodynamics of multi-shell engineering features

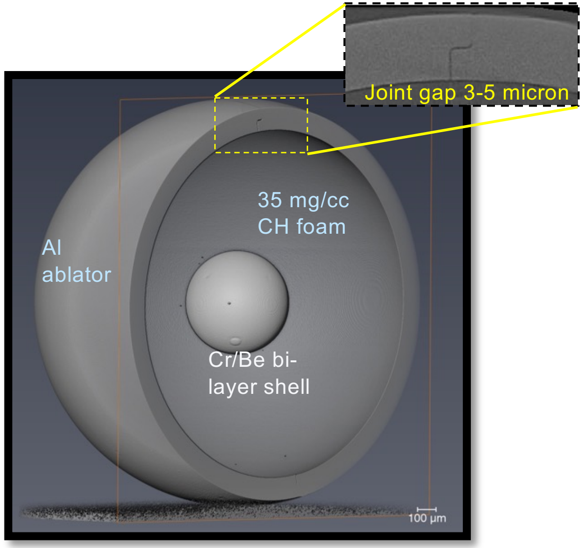
Hydro-growth radiography (HGR) platform enhances our view of feature evolution in the outer shell

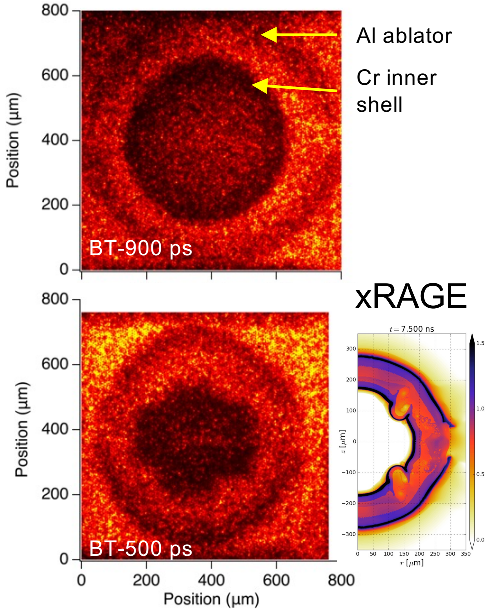


Metrology (CT, Lindsey Kuettner MST-7)

*B. M. Haines et al., Phys. Plasmas 28, 032709 (2021)

Backlighting full double shell provides clear view of feature interaction with metal inner shell





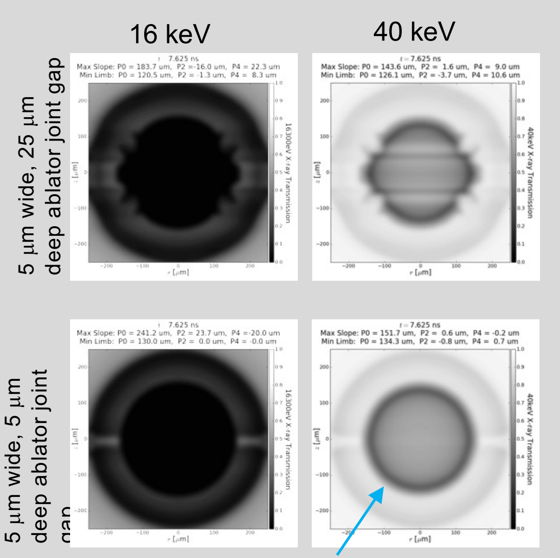
Shot RI: P. Keiter (LANL)
Designer: J. Sauppe (LANL)
Target engineering: T. Cardenas (LANL)

Shape imprinting

Engineering features

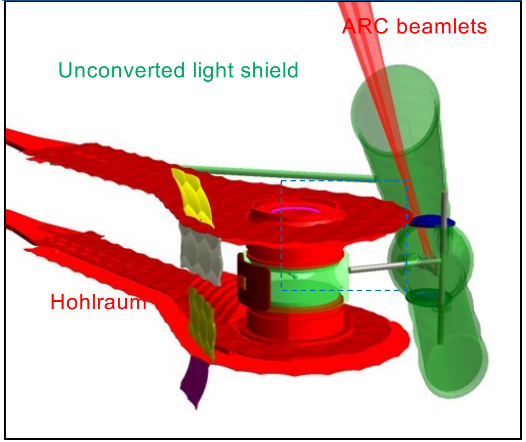
We are developing (LANL-first) high-energy radiography platforms on NIF

40 keV radiography provides clear view of high-Z inner shell (xRAGE simulations)



Object radius is ~150 micron

LANL Dshell platform uses Advanced Radiography Capability (ARC) high-intensity laser



Lead NIF Shot RI: Paul Keiter

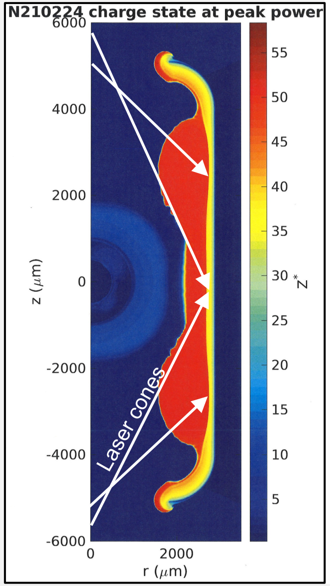
- ***Collected our first ARC data this week!***

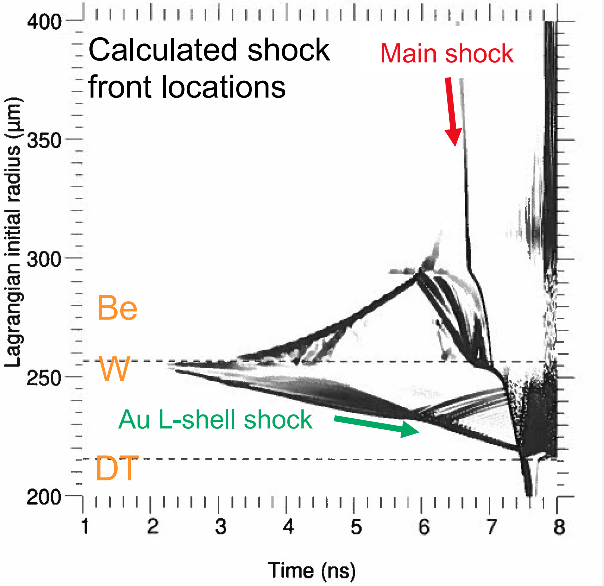
Hard x-ray pre-heat

Optical interferometry (NIF VISAR*) has placed rigorous constraints on state of tungsten pusher at onset of shell collision

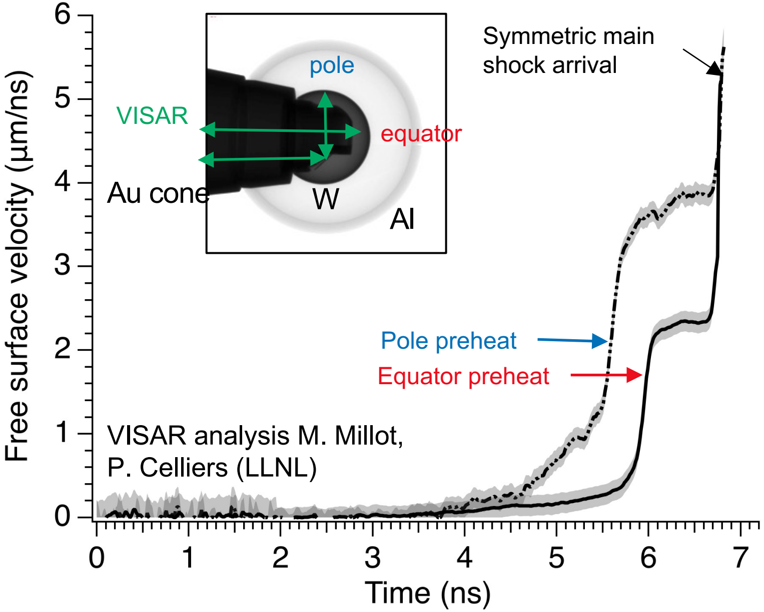
High charge state Au emits L-shell radiation preheating inner shell

xRAGE hohlraum (B. Haines)





Measured W/fuel interface velocity and symmetry due to Au L-shell preheat



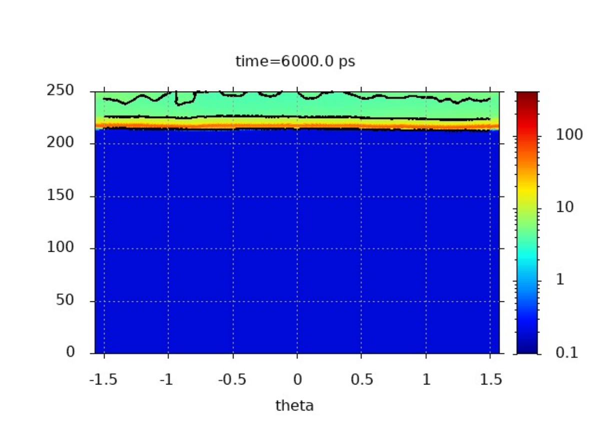
*H.F. Robey, P.M. Celliers et al. Phys Rev Letts. 108 (2012)

Foam/high-Z shell stability

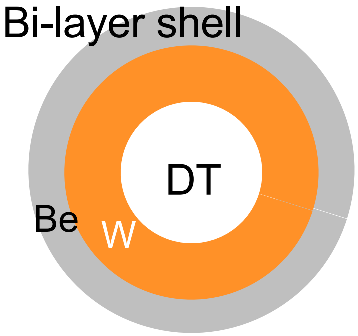
Engineered density gradients[1] are a promising method for controlling instability growth

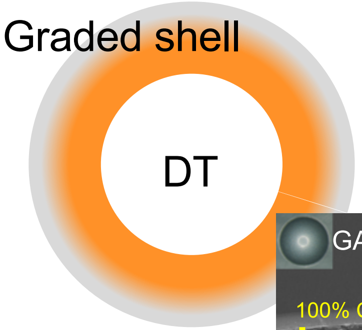
[1] J.L. Milovich, P. Amendt, et al., Phys. Plasmas 11 (2004)

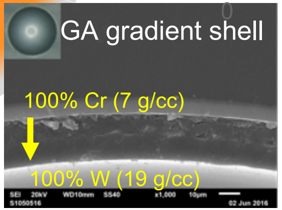
Stabilizing pusher/foam interface is needed to reach high fuel ρR and T_{ion}



xRAGE, Irina Sagert

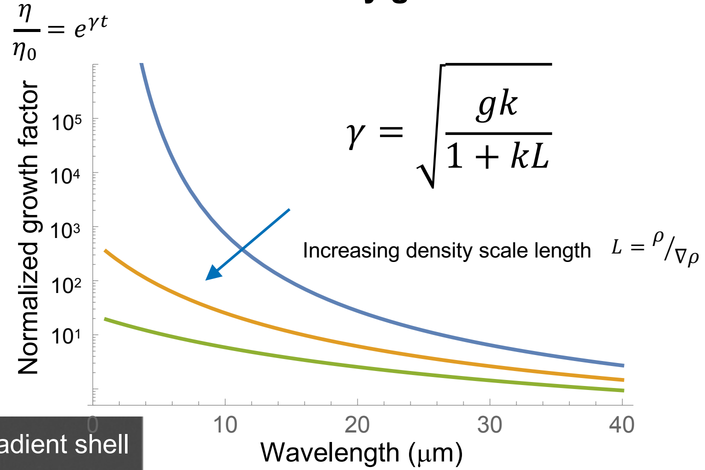






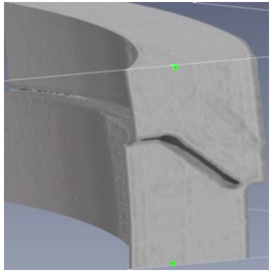
Courtesy Hongwei Xu (General Atomics)

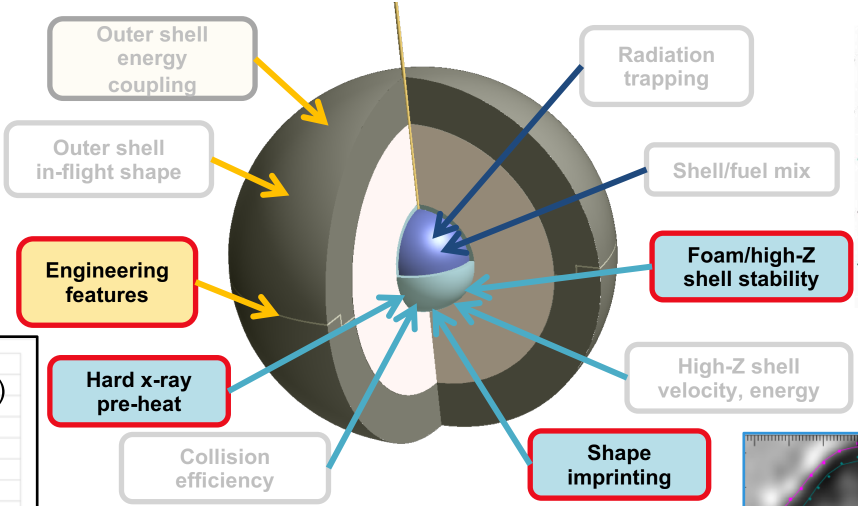
Short wavelengths exhibit greatest reduction in growth factors in presence of density gradient

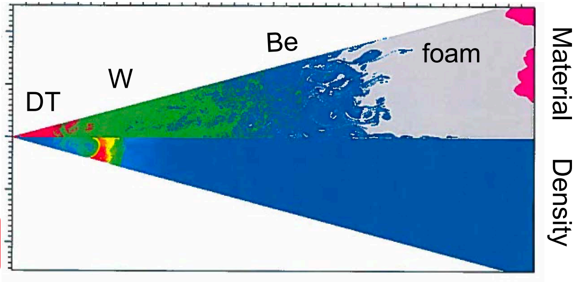


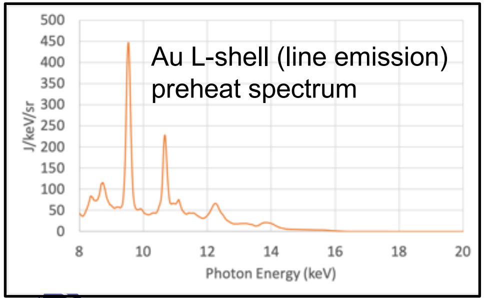
Our research is focused on understanding double shell physics from the outer shell through burn

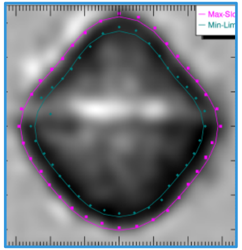
Outer shell joint offset











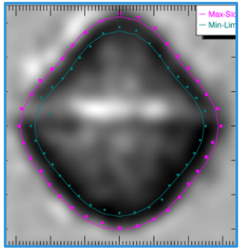
Outer shell radiography

THANK YOU!

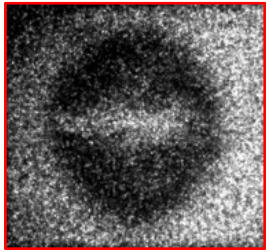
Before we can make full use of advanced hohlraums we must address open physics and engineering questions

Ablator shape asymmetries lead to non-radial flows prior to burn

1.0 MJ

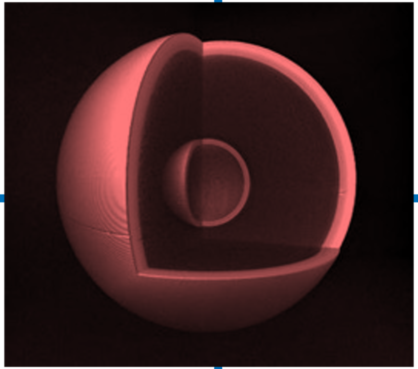


1.5 MJ

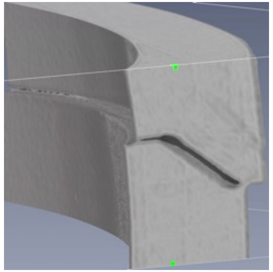


Hard x-ray preheat can decrease performance

L-band multiplier	Yield/1X case	Pusher vel. (km/s)	Fuel ρr/ 1X case
1X	100%	210	100%
2X	95%	207	83%
4X	85%	203	78%

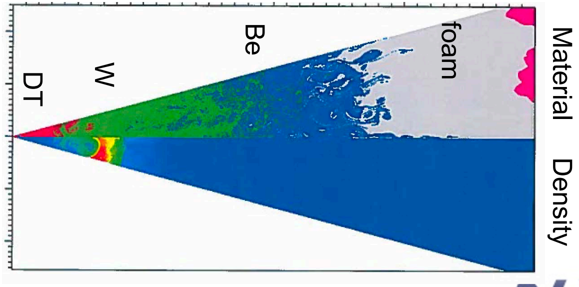


Engineering features can lead to jetting and mix into the fuel



Computed tomography (CT) of as-built Al ablator from hemi-shells

Pusher instability growth



High-Z (tungsten) shells are needed to assess our proximity to ‘robust burn’ regime

For alpha-heating rate to exceed expansion losses at minimum volume

$$T_{keV} > \frac{4}{\left(\rho R_* \, f_{tamp} \, \hat{Q}\right)^{0.4}}$$

Alpha-heating off

ρR (g/cm²)	T (keV)
0.25	> 4.6
0.35	> 3.9
0.60	> 3.1

*Montgomery, Daughton et al., Phys. Plasmas (2018)

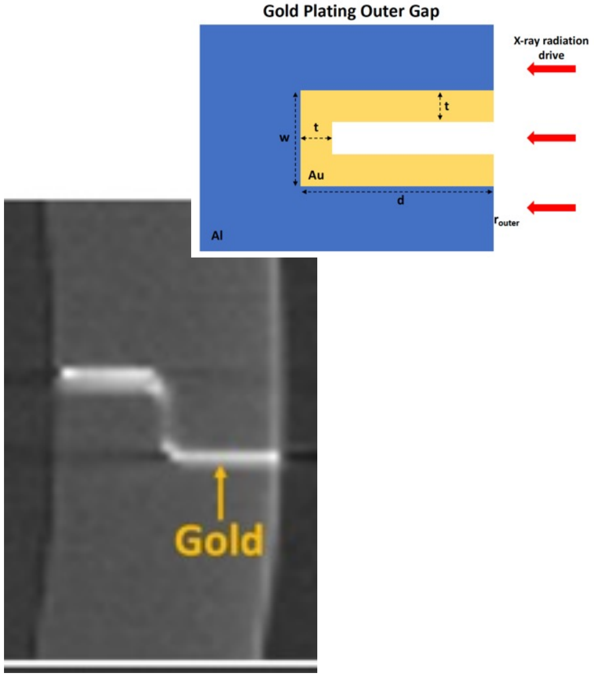
Surrogate CD fuels provide capability to probe nuclear performance without DT filling

Rev. Ramp Pulse with W Inner
(40 μm thick Inner and 40 μm thick Tamper)

Fill	DT	D_2	CD	CD_2
DT Yield	3.88e17	2.08e12	1.68e10	5.04e10
DD Yield	1.94e15	2.33e14	8.07e12	1.90e13
ρR [g/cm²]	0.441	0.563	0.833	0.757
Max Vel. [μm/ns]	215.5	215.3	216.8	216.6
Max KE [kJ]	13.115	13.083	13.185	13.153
No-Burn CR	12.26	11.59	14.79	13.84
No-Burn Prs. [Gbar]	999.53	970.69	1234.77	1164.25
No-Burn T_i [keV]	3.36	3.05	3.10	3.01

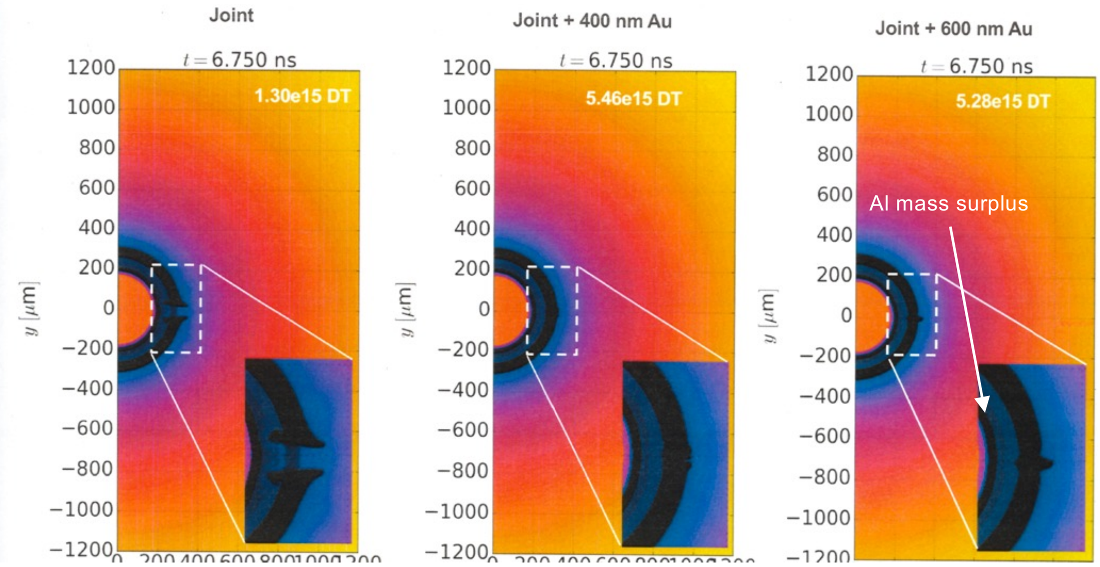
High D-D ion temperatures will indicate robust fuel compression by pusher shell

xRAGE simulations suggest Au coating in gap significantly reduces joint feature growth



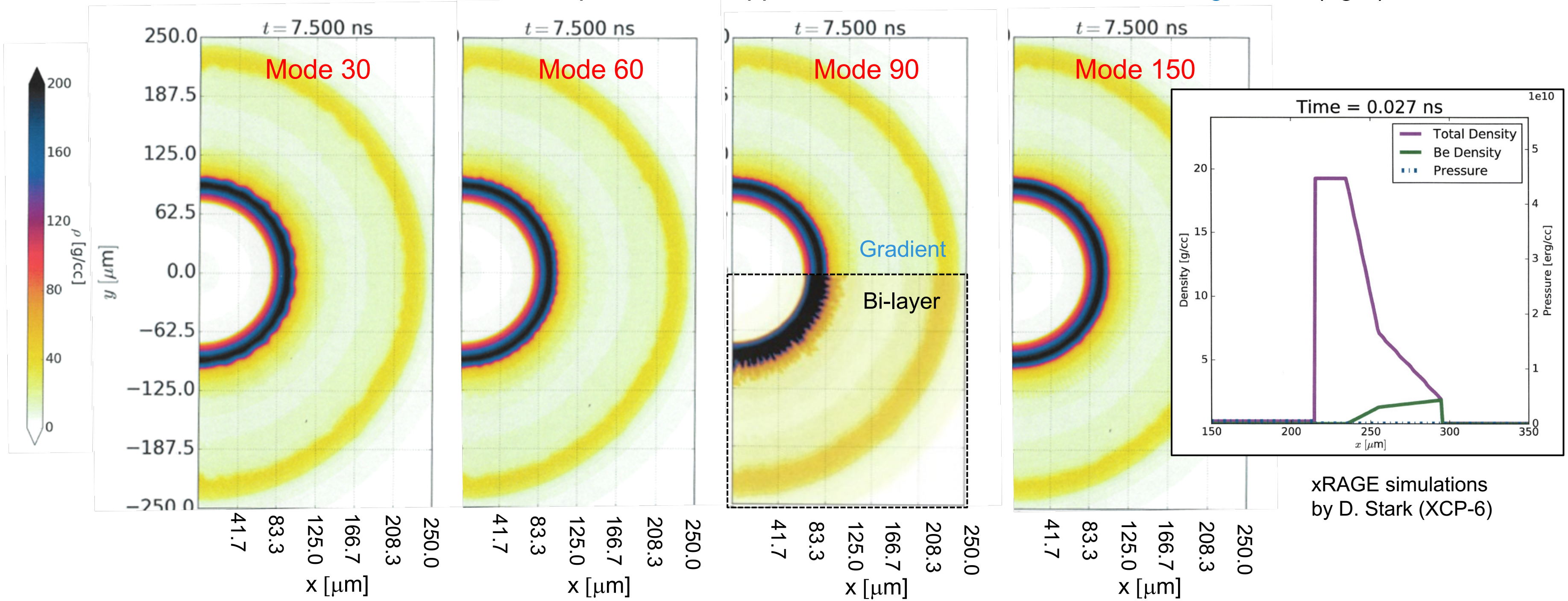
X-ray image of as-built Al shell (Tana Cardenas, MST-7)

xRAGE simulations showing transition from mass deficit to surplus with more Au in gap (D. Stark, XCP-6)



xRAGE graded density simulations predict strong stabilization for mid and high mode numbers

xRAGE simulations of 125 nm perturbation applied at Be/foam interface with Be/W gradient (right)



xRAGE simulations by D. Stark (XCP-6)

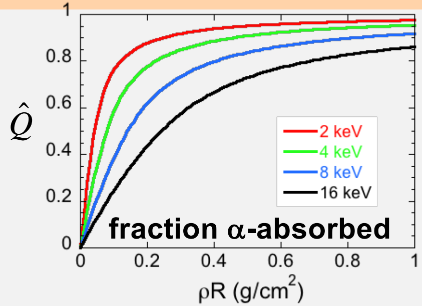
Machine learning (ML) methods currently in use to explore many possible gradient profiles (N. Vazirani, M. Grosskopf)

High-Z shells offer new opportunities to assess power balance in a confined, burning plasma

*Montgomery, Daughton et al., Phys. Plasmas 25, 092706 (2018)

Fusion heating rate must exceed expansion losses

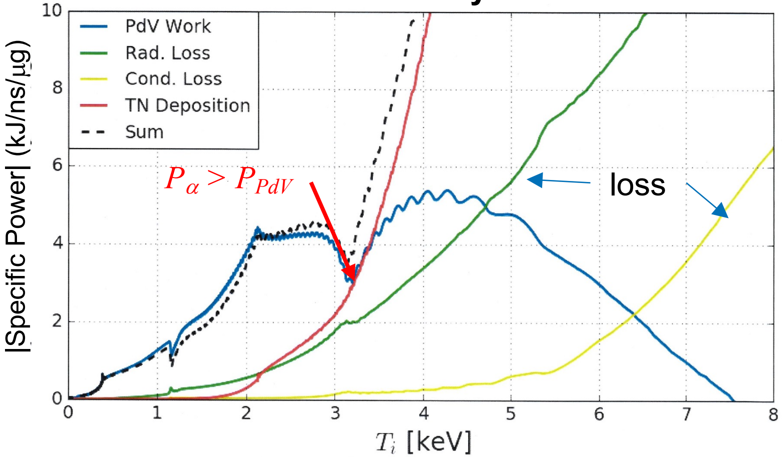
$$\boxed{T_{keV} > \frac{4}{\left(\rho R_* \, f_{tamp} \, \hat{Q}\right)^{0.4}}}$$



- Ensures burn begins before peak compression
- 'Robust' to implosion asymmetries and pusher/fuel mix
- Does not include radiation losses...

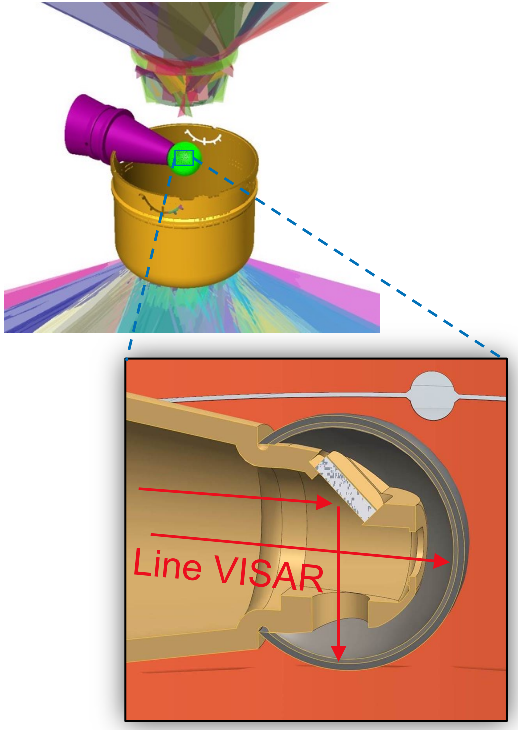
ρR (g/cm²)	T (keV)
0.25	> 4.6
0.35	> 3.9
0.60	> 3.1

How important are radiation losses in a volume burn system?



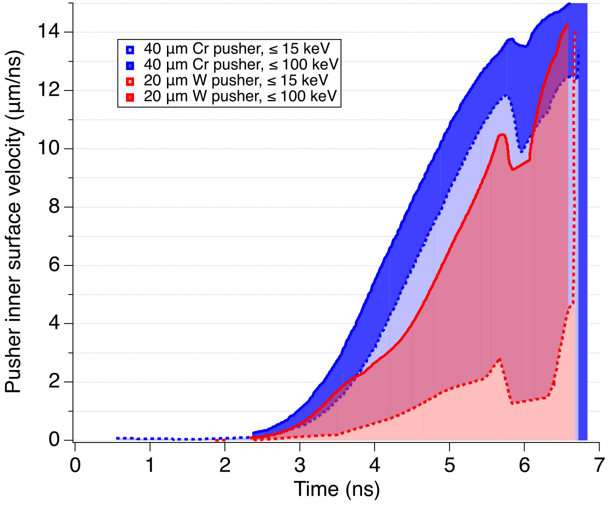
Mass-averaged fuel temperature

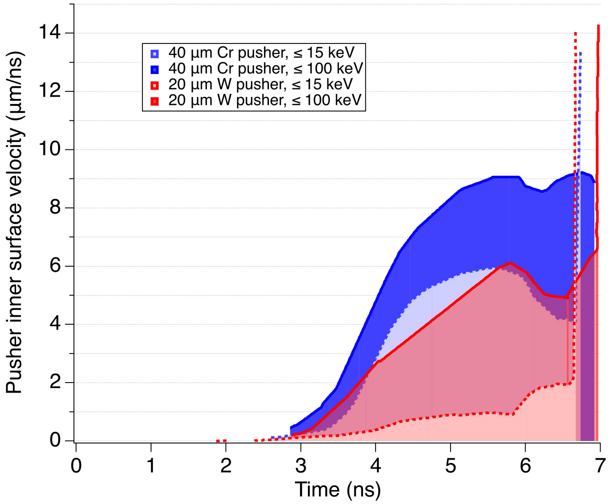
In 2020 we will extend the double shell platform to observe L-shell preheat symmetry using mirrored keyhole



View inside inner shell

HYDRA 2D integrated predictions for inner shell motion at (left) pole and (right) equator

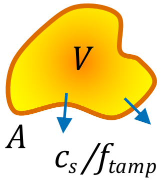




- *W inner shell more sensitive to >15 keV x-rays present*
- *Cr inner shell greater sensitivity to details of L-shell-only spectrum*

Robust burn occurs when fusion heating rate exceeds *PdV* work of the gas on the shell

$$\boxed{\dot{q}_{fus} > \dot{q}_{PdV}}$$



$$R_* \approx 3V/A$$

$$\dot{q}_{fus} = \frac{n_i^2 \langle \sigma v \rangle Q_\alpha V}{M_{DT}}$$

$$\dot{q}_{PdV} = \frac{P}{M_{DT}}\left(\frac{dV}{dt}\right) \approx \frac{P}{M_{DT}}\left(\frac{Ac_s}{f_{tamp}}\right)$$

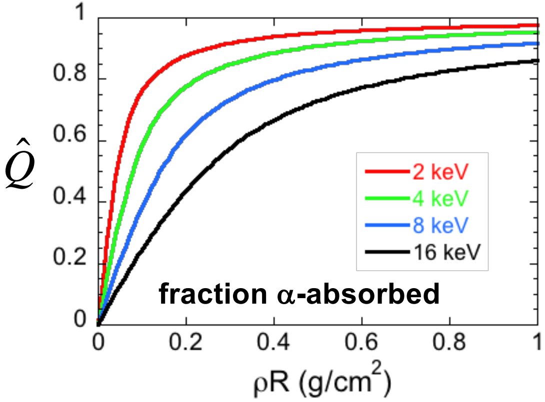
$$\langle \sigma v \rangle \approx 2.2\times 10^{-20} T_{keV}^4 \;\; cm^3/s \quad 2.5 < T_{keV} < 5.5$$

metric for robust burn (similar to fall-line)
- conditions less than → sensitive to asymmetry
- conditions greater than → robust against asymmetry
  - means that burn begins prior to stagnation

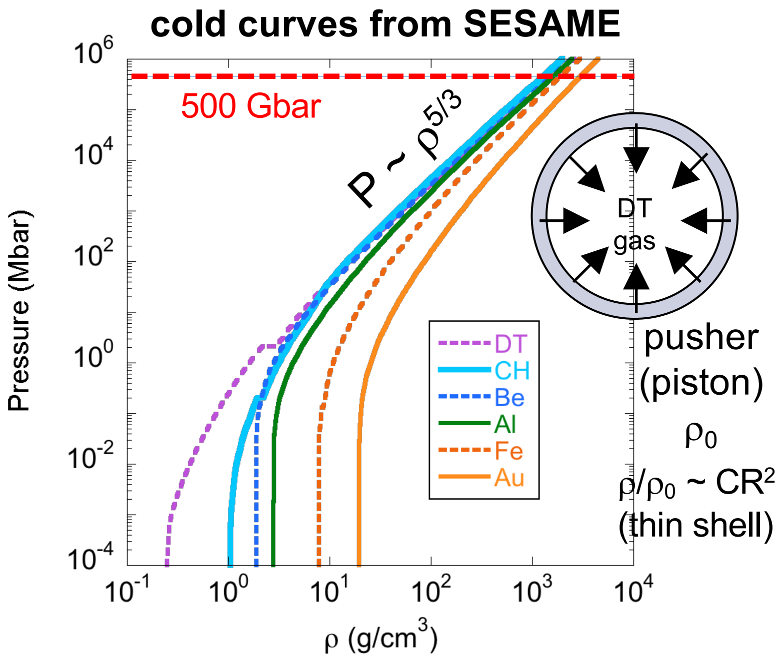
Bill Daughton and David Montgomery (LANL)

no-burn T_i at stagnation

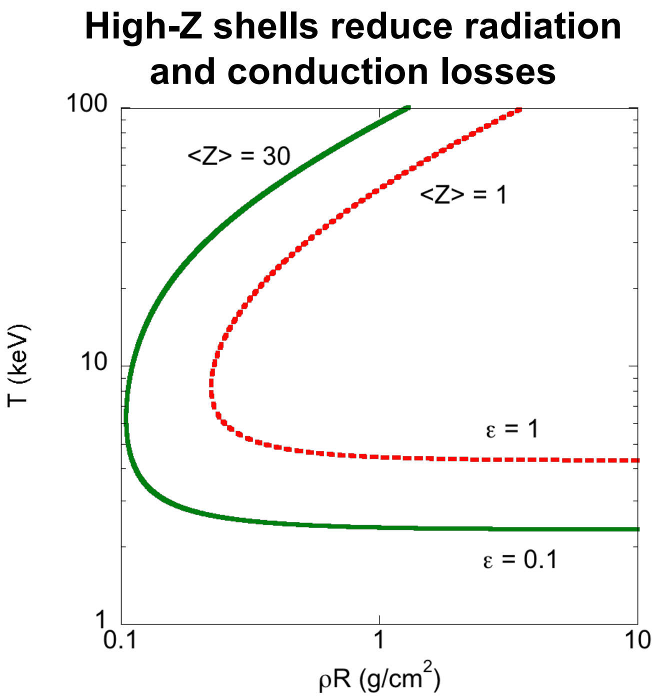
$$\boxed{T_{keV} > \frac{4}{\left(\rho R_* \, f_{tamp} \, \hat{Q}\right)^{0.4}}}$$



Cold Curves of (P, ρ) illustrate why a dense, high-Z pusher may be attractive for ICF

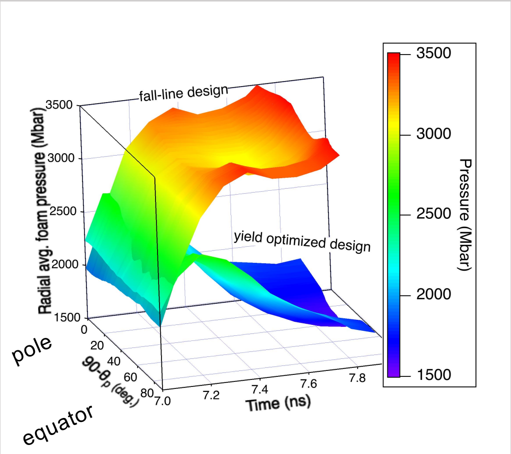


- CR ~ 40 for DT ice pusher
- CR ~ 10 for Au pusher

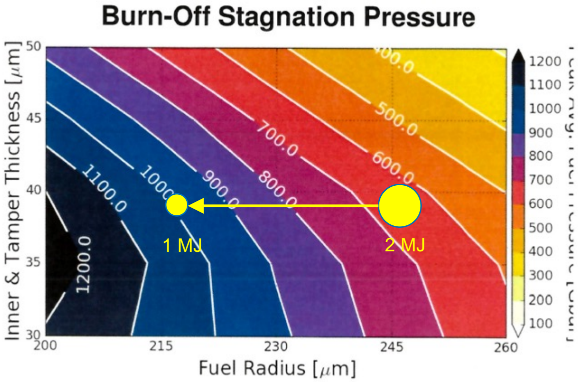


The LANL 1.11 mm design trades-off high 1D yield for higher stagnation temperatures and pressures

Shape imprinting changes with shell aspect ratio (and CR)



- Collision pressure increases, imprint decreases with smaller fuel radius (“fall-line”) design

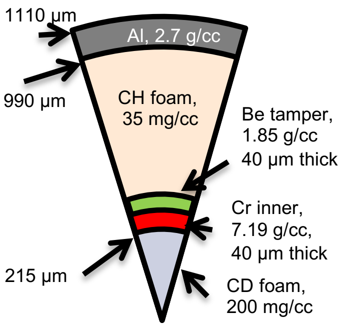


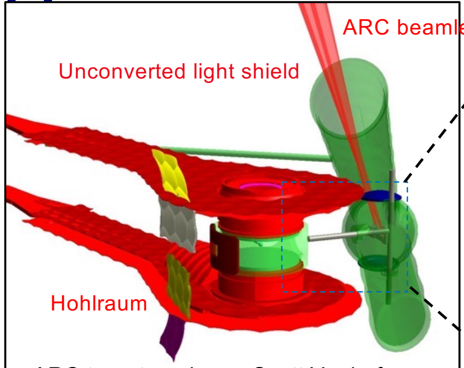
Best fall line ← Higher 1D yield

Simulations from J. Sauppe (XCP-6)
Design by B. Daughton (XTD-PRI)

Double Shell ARC platform requires *intermediate magnification,* high-energy backlig

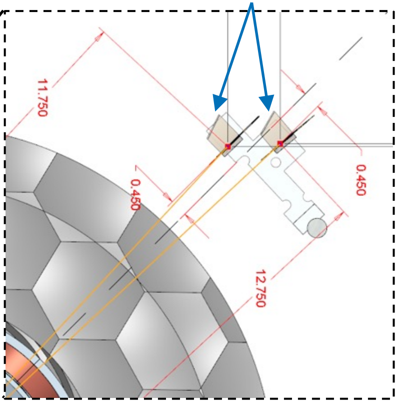
Double shell capsule





ARC target engineer: Scott Vonhof (LLNL)

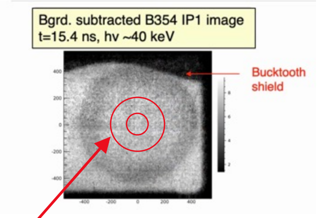
'U-flag' wire backlighters



Comparison of ARC backlighting platforms

	Compton Rad.	DShell ARC	PSS ARC
Object radius (µm)	<100	50-200	200-400
Magnification	>90	50	18.5
Diagnostic axis	90-78	90-315	90-124
BL type (2 ea.)	10 µm Au, U-Flag	25 µm Au, U-Flag	25 µm Au, U-Flag
Targ. Insertion	cryoTARPOS	TARPOS	TARPOS
ARC energy	750 J/beamlet	750 J/beamlet	750 J/beamlet
ARC pulse	30 ps	30 ps	30 ps

N191031 Be/Cr PSS

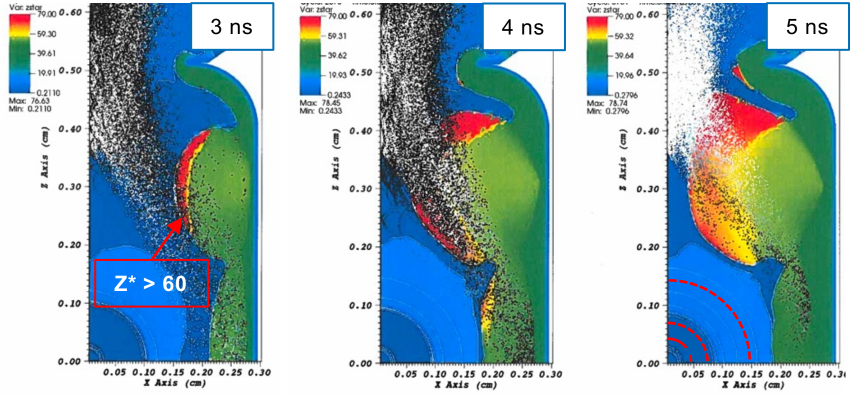


RI: E. Dewald, D. Martinez
Design: S. MacLaren

DShell object range

Double shell VISAR platform allows us to benchmark both preheat and main shock symmetry

Au L-shell radiation emanate from Z* > 60 regions in outer cone Au bubble (HYDRA integrated hohlraum simulations, inner laser cones shown)

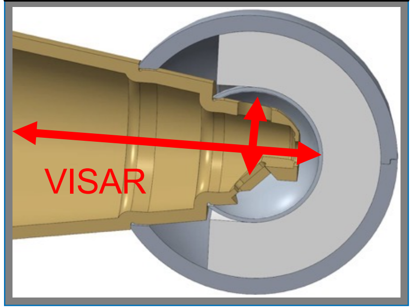


Au bubble scaling[1]

$$\frac{R_{bubble}}{R_{hohlraum}} \sim \sqrt{\frac{E_{picket,outer}}{A_{outer}\rho_{fill}}}\,\frac{\tau}{R_{hohlraum}}$$

[1]DA Callahan et al., Phys. Plasmas (2018)

2-axis NIF VISAR shot coming September 2020



Target engineering: Tana Cardenas, Theresa Quintana, Lindsey Kuettner, Brian Patterson

Constraining the Au L-shell emission helps to further advance hohlraum modeling